Time-Dependent Forgetting in Visual Short-Term Memory

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RUNNING HEAD: Temporal Forgetting in Visual Memory

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Abstract

Whether visual short-term memory can be lost over an unfilled delay, in line with time-dependent forgetting, is controversial. Prior work has yielded mixed results and it is possible that other processes make a bigger contribution to memory loss than the length of the retention interval. The present study explored time-dependent forgetting in visual short-term memory in relation to other factors. In three experiments, participants compared single target and probe objects over a 2 s or 10 s retention interval. The objects across trials were either similar or dissimilar (Experiment 1) and had to be remembered in the presence of an additional distractor (Experiment 2) or under conditions where the amount of time separating trials varied (Experiment 3). In all experiments, the retention interval manipulation made the biggest contribution to performance, with accuracy decreasing as the retention interval was lengthened from 2 s to 10 s. These results pose problems for interference and temporal distinctiveness models of memory but are compatible with temporal forgetting mechanisms such as decay.

Keywords

Visual short-term memory, forgetting, decay, interference, temporal distinctiveness.

In recent years, there has been much debate about the mechanisms underlying forgetting in short-term and working memory (e.g. Lewandowsky, Oberauer & Brown, 2009; Oberauer & Lewandowsky, 2014). A broad distinction can be made between theories that allow a role for time in forgetting (temporal models of memory loss), and those that reject a temporal component and attribute forgetting to interference processes (see Farrell et al., 2016; Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012). A third class of models, based around temporal distinctiveness, incorporate both time and interference components, but forgetting is attributed to proactive interference (e.g. Brown, Neath, & Chater, 2007).

Evidence for temporal forgetting in situations lacking overt distraction is theoretically relevant, as it would be incompatible with interference models. In visual memory, such forgetting can be explored using change detection procedures, where participants must remember an array of visual stimuli and then determine whether any changes have been made to that array. Varying the length of the retention interval separating the target stimuli from the test array can then be used to monitor memory loss. Keeping this interval free from external interference is important, as any decline in performance would suggest some role for time in forgetting.

This approach was adopted by Ricker and Cowan (2010, 2014) and they found that change detection performance declined as the retention interval was lengthened (particularly between 1 s and 6 s). Furthermore, time-based forgetting of visual material has been documented in other experiments and for a variety of different stimuli, including orientation and colour (Pertzov, Bays, Joseph, & Husain, 2013; Rademaker, Park, Sack, & Tong, 2018), texture (e.g. Gold, Murray, Sekuler, Bennett, & Sekuler, 2005), complex, unfamiliar stimuli (McKeown, Holt, Delvenne, Smith, & Griffiths, 2014; Mercer & Duffy, 2015) and faces (e.g. Krill, Avidan, & Pertzov, 2018; Rademaker et al., 2018). Memory for movement may also be subjected to time-based forgetting (e.g. Hesse & Franz, 2010).

Such forgetting could be attributable to a decay process, which degrades a memory trace over the passage of time (see Ricker, Vergauwe, & Cowan, 2016). Decay is a component of several theories of visual memory (e.g. Lohmann, Herbort, & Butz, 2013; McKeown et al., 2014; Sakai & Inui, 2001) and it has been used to explain a variety of phenomena, including the loss of precise perceptual information (see Gold et al., 2005), the diminishing ability to detect changes to visual arrays at longer intervals (e.g. Ricker & Cowan, 2010, 2014) and the retro-cueing effect. The latter phenomenon is demonstrated when a cue presented after a memory array improves retrieval when it informs the participant of the object that should be remembered (see Souza & Oberauer, 2016, for a review). Some authors have argued that this retro-cueing effect emerges because the cued object can be protected from degradation otherwise caused by decay (e.g. Matsukura, Luck, & Vecera, 2007; Pertzov et al., 2013).

However, in their consideration of benchmarks in working memory tasks, Oberauer et al. (2018) argued that findings of temporal forgetting of visual information over unfilled delays is both inconsistent and ambiguous. Indeed, widely different forgetting rates have been reported in the literature, with some studies showing very rapid forgetting (e.g. Pertzov, Manohar, & Husain, 2017) and others reporting a more gradual decline (e.g. Mercer & Duffy, 2015). There are also cases where no time-dependent forgetting has been observed (e.g. Magnussen & Greenlee, 1999; Magnussen, Greenlee, Baumann, & Endestad, 2010; Soemer, 2019, Experiment 3). In a discussion of such work, Shin, Zoi, and Ma (2017) found little evidence for temporal forgetting for spatial frequency, speed and some aspects of motion (e.g. direction and coherence) in the existing literature.

One possibility is that time-dependent forgetting is more likely to be observed when multiple visual objects must be remembered, whereas a single object may be protected from temporal loss. Typically, studies that have not found time-dependent forgetting have used single, simple stimuli (e.g. Magnussen et al., 2010) and Pertzov et al. (2017) confirmed that individual objects can be remembered with high precision over a delay. However, forgetting over time has been reported for individual stimuli in some cases (e.g. Rademaker et al., 2018), whereas in other studies forgetting has not been shown for multiple items (e.g. Soemer, 2019, Experiment 3). Capacity therefore cannot be the only factor affecting the loss of visual memories over time, but it may play a role.

Furthermore, even if visual information is subjected to forgetting over a delay, there may be other factors that make a larger contribution to memory loss. Such ideas have been echoed in the verbal memory literature (Berman, Jonides, & Lewis, 2009; Campoy, 2012) and to fully understand time-based forgetting, consideration should be given to the wider context within which visual memories are formed. This includes the physical distinctiveness of stimuli, relating to the structural similarity between the target memory and other items, and temporal distinctiveness, relating to the temporal proximity of the target memory and other items. The role of retroactive interference, involving post-encoding distraction, may also contribute to memory loss more substantially than the length of the retention interval.

The present study aimed to assess time-dependent forgetting in visual short-term memory in relation to these wider contextual factors. Experiment 1 explored physical distinctiveness and its contribution to forgetting, whereas Experiment 2 investigated the role of distraction in influencing memory loss. Experiment 3 manipulated temporal distinctiveness and the possibility of slowing or preventing the loss of a visual memory over time. Unlike many earlier studies, the present study required participants to remember just one item on each trial. The advantage of this arrangement is its reduction of concurrent interference (i.e. competition between different to-be-remembered items within an array is avoided), though retention of a single object may be much easier than memorising multiple objects. To offset this concern, participants were required to remember fine details in a complex, unfamiliar stimulus. This is influenced by an approach used in previous studies, where stimuli are unfamiliar to participants (e.g. Ricker and Cowan 2010), and this may help control covert rehearsal (it may be hard to rehearse non-verbal stimuli, allowing forgetting to occur). The use of multi-component stimuli also allows time-dependent forgetting to be explored for complex and rich visual information, extending the type of visual stimuli that have been investigated.

Experiment 1

The first experiment investigated temporal forgetting within a physical distinctiveness framework. Here physical distinctiveness concerned the similarity between the items being used in the task, and it was expected that low physical distinctiveness (denoting high similarity amongst to-be-remembered items) would be advantageous. Prior studies have shown that the ability to detect changes to visual arrays is improved when the to-be-remembered targets are similar. Lin and Luck (2009) recorded heightened accuracy in a colour change detection task when the objects in the array were similar (e.g. all red), in comparison to when they were dissimilar. Analogous findings have been reported in other studies too, such as Johnson, Spencer, Luck, and Schöner (2009), Makovski, Watson, Koutstaal, and Jiang (2010), Mate and Baqués (2009), Sanocki and Sulman (2011) and Zhang, Li, Wang, and Che (2016).

Direct repetition of a stimulus within an array can also improve change detection performance, but only if the target and repeated items are spatially close (Peterson & Berryhill, 2013). Similarly, Morey, Cong, Zheng, Price, and Morey (2015) found evidence for a colour sharing bonus in visual working memory. Participants had to remember an array of coloured squares and then determine whether a change had been made to that array. On some trials, a colour was repeated in the array. Capacity estimates were higher when there was a repetition, particularly when the probed item was one of the duplicated colours. Beneficial effect of stimulus repetition was reported by Shimi and Logie (2019) too. Participants encoded arrays of objects as part of a change detection task and repeating the array throughout the experiment was beneficial to performance. In particular, there was evidence of learning throughout the first 40 trials.

According to Sims, Jacobs and Knill's (2012) ideal observer analysis view, encoding is better in a low variance environment, where there is minimal variability amongst stimuli being remembered. Research has shown that greater similarity amongst successive stimuli within a list can reduce recognition errors (e.g. Kahana & Sekuler, 2002; Nosofsky & Kantner, 2006) and Viswanathan, Perl, Visscher, Kahana, and Sekuler (2010) referred to this as the homogeneity effect. The present experiment extended this idea by investigating similarity *across* trials (rather than within lists of items or within the array of to-be-encoded stimuli). Following findings from Shimi and Logie (2009; see also Logie, Brockmole, and Vandenbroucke, 2009), visual information may persist across trials, leading to learning and an improvement in performance. Exposure to similar stimuli across multiple trials would increase participants' familiarity with, and knowledge of, the type of stimuli being remembered. Stored knowledge can influence visual memory (see Brady, Konkle, & Alvarez, 2011, for a review) and familiarity with stimuli improves change detection performance (Xie & Zhang, 2017). Participants can also implicitly learn regularities about visual stimuli to which they are exposed (Brady, Konkle, & Alvarez, 2009), so a low physical distinctiveness context, in which items across trials resemble each other, may have a positive effect on retention. Whether this can influence time-dependent forgetting is, however, uncertain.

In the current experiment, participants were asked to memorise a single complex object over a retention interval lasting 2 s or 10 s. At the end of the delay, another object was presented and the task was to determine whether it was the same as the image shown earlier. In the homogeneous condition (low physical distinctiveness), stimuli were very similar across trials whereas in the heterogeneous condition (high physical distinctiveness) they were much more diverse. Based on the findings reviewed above, performance in the homogeneous condition should exceed that in the heterogeneous condition, but the key issue concerned time-dependent forgetting. Experiment 1 aimed to assess temporal models of forgetting and determine whether any forgetting over the retention interval could be alleviated according to the physical distinctiveness of an object. Temporal models of forgetting expect a clear decline in performance across the retention interval, regardless of physical distinctiveness, due to the ongoing degradation of the memory trace over time. As such, models relying on a decay process would expect a reduction in performance as the retention interval was extended in both the homogeneous and heterogeneous conditions. Alleviated forgetting in the homogeneous condition would therefore be problematic for decay theory, and Experiment 1 provided an opportunity to test this possibility.

Method

Participants

Thirty-two participants aged between 18 and 34 (M = 21.76, SD = 3.73) volunteered. All individuals were staff or students from the University of Wolverhampton, and a criterion of participation was self-reported normal or corrected-to-normal vision. Students received participant pool credits for completing the experiment and provided written informed consent before undertaking the procedure. The sample size was informed by a prior study using the same stimuli that documented time-dependent forgetting over 10 s with 30 participants (Mercer, 2014).

Materials

The stimulus set was derived from the Fribbles database (stimulus images courtesy of Michael J. Tarr, Center for the Neural Basis of Cognition, Carnegie Mellon University, http://www.tarrlab.org/). Fribbles are complex, three dimensional objects that contain a central body and four appendages (a head, legs and two parts of a tail; Barry, Griffith, De Rossi, & Hermans, 2014). The different Fribbles are arranged into three families (A, B, and C) and there is no overlap between items across families (i.e. they are completely distinct). However, each family comprises four different species (1, 2, 3, and 4). The species within a family share the same body, but the appendages are dissimilar – see Figure 1. Aside from allowing systematic manipulation to the Fribble stimuli, another major advantage is their complexity, which may make covert rehearsal difficult.

The fourth species of family A was randomly chosen to serve as the stimulus set for the homogeneous condition, but the same Fribble was never used on more than one trial. Thus, while items within the homogeneous condition looked very similar, there was no direct repetition of any stimuli across trials. This was expected to eliminate item-specific proactive interference (e.g. Makovski & Jiang, 2008; McKeown et al., 2014; Mercer & Duffy, 2015). To create the heterogeneous condition, objects from the remaining 11 family/species were used. This allowed for a lower degree of overlap for items across trials.

Each condition contained 12 trials on which the target and probe were identical ("Same" trials) and 12 trials on which the target and probe differed in a subtle way ("Different" trials). When the two Fribbles differed, they were drawn from the same family and species, but did not share two of their four appendages. This is known to make the task challenging, without causing floor effects (see Mercer, 2014, 2018). As each Fribble has four appendages and two were changed on "Different" trials, there were six possible ways of manipulating the stimuli (e.g. a change to the head and tail 1, or a change to the legs and tail 2, etc.). Each type of change occurred twice within each condition.

When determining the number of trials per condition, a balance needs to be found between ensuring sufficient data are collected while preventing an overly long procedure that could introduce fatigue effects. Twenty-four trials were used in each condition as this allowed each of the twelve major Fribble types (individual species from the four families) to be presented twice, and 24 trials has previously been shown to be capable of detecting time-dependent forgetting (Mercer, 2014, Experiment 2). It also meant the total length of the procedure was reasonable.

In addition to the Fribbles, a mask consisting of a series of overlapping circles of different textures and colours was employed to eliminate any contribution from sensory memory (Saults & Cowan, 2007).

"Figure 1 about here"

As participants' attention may fluctuate over the course of the experiment, particularly towards the latter part of the procedure, the probe capture method for assessing task-unrelated thought was used (see Smallwood & Schooler, 2015). This involves interrupting participants during a task and asking them to state whether they are thinking about the current task at that moment. In this experiment, participants were simply asked "Are you mind wandering?" twice in each condition, at random points. This was used to estimate participants' engagement with the task and frequency of task-unrelated thought.

The experiment was run within a small cubicle using a PC and SuperLab (Version 4.5) software. Stimuli were displayed on a HannsG HP191 19-in. LCD monitor and responses were recorded on a keyboard.

Design and Procedure

The experiment employed a 2 (retention interval: 2 s vs. 10 s) x 2 (condition: homogeneous vs. heterogeneous) repeated measures design. The procedure was explained to participants and mind wandering was defined before they began. They were seated approximately 60 cm from the monitor and completed four practice trials before commencing the real experiment. During experimental trials, a central fixation cross was displayed for 100 ms and immediately followed by the target item. The target remained in the centre of the screen on a white background for 700 ms and, after a blank delay of 250 ms, the mask was shown for 100 ms. After the offset of the mask, there was an unfilled gap lasting 1.65 s or 9.65 s, after which the probe item was displayed. The task was to determine whether the target and probe were the same (by pressing “S”) or different (by pressing “D”). The probe remained on screen until participants responded or after 2 s had elapsed. Participants were encouraged to respond quickly, but without sacrificing accuracy. The next trial began after a 400 ms inter-trial interval.

On two trials within each condition, participants were not shown the probe at the end of the retention interval, but given the mind wandering probe instead. The question remained on screen until participants had responded by pressing either “Y” (“Yes, I am mind wandering”) or “N” (“No, I am not mind wandering”). This was used to assess participants’ focus over the course of the experiment.

Participants completed the experiment in blocks, with each block containing trials from one of the four conditions. The order of blocks was randomly determined, as was the order of trials within each block. However, due to the length of the two conditions featuring a 10 s retention interval, they were each divided into two smaller blocks comprising 12 trials (six "Same" and six "Different"). After every two blocks, participants could take a short break and the entire experiment lasted approximately 30 minutes.

Results

Preliminary Analysis

Two participants had numerous missing responses (36.46% and 43.75% absent responses, respectively). Another two individuals had a smaller, but still substantial, number of missing responses (16.67% and 20.83% missing, respectively), unusually quick responses (< 150 ms) on some other trials, and overall poor performance. These four participants were therefore excluded.

Accuracy on the task was denoted by *A'*, which offers a bias-free index of sensitivity that can also handle perfect accuracy (e.g. 100% hits or 0% false alarms). To calculate *A*', Snodgrass, Levy-Berger, and Haydon's (1985) formula was used, with 0.5 denoting chance performance and 1 denoting perfect performance. Hits were classed as the proportion of Same trials on which the participant correctly responded "Same", whereas false alarms were classed as the proportion of Different trials on which the participant incorrectly responded "Same".

A mean *A'* score was then calculated by averaging scores across the four conditions. This variable was then screened for outliers and one participant was detected whose average performance was over 3 *SD*s below the mean. This participant was removed. Finally, for the remaining 27 participants, trials lacking a response within the 2 s time limit were excluded from the analysis. This represented 4.75% of total trials, on average.

The extent of task-unrelated thought is shown for each mind wandering probe in Table 1. Responses were coded as 0 (“No” response) or 1 (“Yes” response), and the overall mind wandering score was the sum of responses to the eight probes. “Yes” responses to the probes were common (median number of “Yes” responses = 3, or 38% of probes) but tracking mind wandering across the experimental trials using Cochran’s *Q* test revealed no significant differences in yes/no responses across the procedure, $\chi^2(7) = 4.51$, $p = .72$.

“Table 1 about here”

Task Performance

“Figure 2 about here”

A’ scores in each condition are shown in Figure 2. A 2 (retention interval: 2 s vs. 10 s) x 2 (condition: homogeneous vs. heterogeneous) Bayesian repeated measures ANOVA was then used to assess performance, with JASP (JASP Team, 2018). Bayesian analyses can quantify support for the null and alternative hypotheses, and Bayesian ANOVAs can also be used to find the model with most support. The Bayesian ANOVA conducted here included both a model comparison, in which all effects within the model are assessed (see appendices), as well as more specific analysis of effects. Analysis of effects are particularly useful for considering main effects and interactions, and formed the primary tool here (though the full model comparison can be found in Appendix 1). The analysis of effects yields a $BF_{Inclusion}$

score, which can be used to assess whether there is support for a particular effect/interaction within the model – i.e. are data more likely in a model with a specific effect than a model without that effect? Interpretation of $BF_{Inclusion}$ scores can follow that for other Bayes factors (see Wagenmakers, Love, et al., 2018), where values greater than 3, 10 or 100 show moderate, strong or extreme evidence for a particular model. Values less than 0.33 highlight models with no reliable support from the data, whereas values in the intermediate region (0.33-3) are insensitive or inconclusive. Finally, 95% *CI*s were calculated, following Jarmasz and Hollands (2009) for a repeated measures design, and *CI*s are reported in brackets following means (see also Figure 2).

There was a clear decline in performance as the retention interval was extended from 2 s to 10 s. This effect was seen in both the homogeneous and heterogeneous condition, although accuracy was slightly higher in the homogeneous condition. The Bayesian ANOVA's analysis of effects, shown in Table 2, confirmed that there was extreme support for the model including retention interval. Mean *A'* dropped from 0.80 (0.76, 0.84) at the 2 s interval to 0.69 (0.65, 0.73) at 10 s. Performance was also better in the homogeneous (M = 0.77 [0.73, 0.81]) than heterogeneous (M = 0.71 [0.67, 0.75]) condition, and there was some moderate evidence for retaining this effect in the model. Conversely, there was no justification for including the interaction in the model, and accuracy in both conditions declined at a similar rate over time.

"Table 2 about here"

Discussion

Experiment 1 found strong time-dependent forgetting, with the ability to discriminate the target and probe declining substantially at the 10 s retention interval. Accuracy was also modestly better in the low physical distinctiveness situation (the homogeneous condition) rather than a high physical distinctiveness situation (the heterogeneous condition).

The small advantage shown in the homogeneous condition may have been due to the involvement of long-term memory (LTM). Repeated exposure to a similar set of stimuli may allow a template of the objects to be developed and held in LTM, and this template could have guided responding. Related to this point, increased experience with the specific stimulus type used in the homogeneous condition may have heightened its familiarity. If so, participants would have become better at identifying the type of changes that occurred to the four appendages.

Nonetheless, the homogeneity effect was subtle. When considering the Bayesian model comparison, which uses the traditional Bayes factor (BF_{10}, see Appendix 1), data were 2.5 times more likely under the alternative than null hypothesis. So, there was support for the alternative hypothesis, but this was not very convincing. This may support Shimi and Logie's (2019) suggestion that there is a residual trace that persists across trials, developing with repetition and leading to learning, but it is weak.

Conversely, data were over 1,300 times more likely under the alternative than null hypothesis when considering the retention interval effect. It was temporal forgetting that dominated the model and, of most importance to the present study, both conditions suffered from equivalent time-dependent forgetting. This effect is congruent with a decay process and replicates other results showing time-dependent forgetting in visual memory (e.g. Gold et al., 2005; Hesse & Franz, 2010; Mercer & Duffy, 2015; Pertzov et al., 2017; Ricker & Cowan, 2010, 2014). Stimulus homogeneity was not capable of reducing or preventing temporal forgetting.

Experiment 2

In Experiment 1, clear forgetting over the retention interval occurred, but task accuracy remained well above chance. It is possible that the presence of additional interference within the retention interval would increase time-dependent forgetting. Specifically, while interference effects may be relatively modest at a short retention interval, their impact may be more substantial over longer retention intervals, leading to a larger decline in performance than a control condition lacking any external interference. The second experiment therefore assessed the impact of a post-encoding distractor and intended to directly compare the effects of retroactive interference and time within the same study. Whilst these two mechanisms have been shown to affect visual memory (e.g. Makovski, Shim, & Jiang, 2006; Ricker & Cowan, 2014), time-based forgetting may be more prominent in the presence of additional retroactive interference.

When considering retroactive interference in visual short-term memory, two mechanisms may be involved: interruptions and distractions (Clapp, Rubens, & Gazzaley, 2010). Interruptions require participants to engage in an attentionally-demanding secondary task during the retention interval (e.g. Clapp et al., 2010), whereas distractions involve passive exposure to irrelevant information (e.g. Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999; Logie & Marchetti, 1991). The present study explored a possible connection between distraction and temporal forgetting, but a secondary aim was to assess the role of target-distractor similarity. According to the similarity assumption (Sun et al., 2017), distraction is more damaging when there is some similarity between the target and distractor, and there is empirical support for this idea (Andrade, Kemps, Werniers, May, & Szmalec, 2002, Experiment 5; Blalock, 2013; Borst, Ganis, Thompson, & Kosslyn, 2012; Tremblay, Nicholls, Parmentier, & Jones, 2005; Vogel, Woodman, & Luck, 2006). However, there is also evidence that a dissimilar distractor can disrupt visual memory (e.g. Mercer, 2018; Sun et al., 2017).

Of particular importance was the interaction between the distractor and the retention interval length. Specifically, the distractor may be associated with lower performance than a no-distractor control at longer retention intervals, but to date there appears to have been little attempt to test this possibility in visual short-term memory. Furthermore, the limited research that is available casts doubt on this idea. Mercer (2018, Experiment 1) placed a distractor either 200 ms or 1.5 s after the target and varied the length of the retention interval (either 2.4 s or 6 s). A dissimilar distractor was capable of disrupting performance when placed 1.5 s after the target, but this was not dependent on the length of the retention interval, although the longest interval may have been too short to observe forgetting.

Experiment 2 used a similar set-up to Experiment 1, where participants compared target and probe objects over retention intervals lasting 2 s or 10 s. In the control condition, the interval contained a mask, but was otherwise unfilled (matching the heterogeneous condition of Experiment 1). In the experimental conditions, a single distractor object was placed half way into the interval. This was either similar or dissimilar to the target.

Temporal models of forgetting would predict performance to decline as the retention interval was lengthened, whereas retroactive interference theory expects poorer performance when a distractor was present, rather than absent. Based on prior research (e.g. Blalock, 2013; Borst et al., 2012), the similar distractor was predicted to lead to a larger decrease in accuracy, in comparison with the dissimilar distractor, though a dissimilar distractor may still be disruptive (Mercer, 2018; Sun et al., 2017). Of most interest was the interaction between the distractor and retention interval, with enhanced time-based forgetting being possible when an irrelevant distractor is present.

Method

Participants

Thirty students from the University of Wolverhampton volunteered for the experiment. Participants were aged between 19 and 58 (M = 25.3, SD = 8.99) and received participant pool credits for completing the study. A criterion of participation was normal or corrected-to-normal vision, and all individuals provided written informed consent before beginning the procedure. The sample size was intended to be similar to Experiment 1.

Materials

Stimulus arrangements were identical to the heterogeneous condition of Experiment 1, except a new set of Fribbles were used. Two additional conditions were included, which involved an irrelevant distractor Fribble inserted into the middle of the retention interval. The similar distractor was selected from the same family as the target, but differed in species. This meant that the target and distractor shared the same central body as the target, but not their appendages. The dissimilar distractor came from a different family to the target, and therefore there was no overlap between the stimuli (see Figure 3). Distractor Fribbles were pseudo-randomly selected, but each Fribble family/species was used twice in each condition. In addition, the stimuli serving as the target and probe were drawn from the full range of Fribbles in all conditions (hence there was no homogeneous condition in this experiment). In total, 312 different Fribbles were used on the experimental trials. The mask and equipment matched Experiment 1.

Design and Procedure

The experiment employed a 2 (retention interval: 2 s vs. 10 s) x 3 (distractor type: similar vs. dissimilar vs. no distractor) repeated measures design. The structure of trials was identical to Experiment 1 and again included 24 trials per condition, but a distractor was presented for 700 ms in some conditions. The distractor was placed halfway into the retention interval (i.e. after 1 s or 5 s) and could be ignored, though participants were instructed to keep their eyes open and on the screen throughout the trials.

In an attempt to reduce proactive interference, the inter-trial interval (ITI) matched the length of the retention interval. This was to allow this experiment to focus on the effects of retroactive interference and reduce the potentially detrimental effect of stimuli seen on the previous trial (but see Experiment 3). Participants were given up to 3 s to respond, which was designed to reduce the number of non-responses seen in Experiment 1, and the mind wandering probes were removed.

Conditions with a distractor were completed separately to those without a distractor, trials with a 2 s retention interval were completed in single blocks, whereas those with a 10 s delay were completed in three individual blocks comprising eight trials (four “Same” and four “Different”). This led to the creation of 12 stimulus blocks. Participants were told whether the block would include a distractor and the order of blocks/trials was randomised. After every four blocks participants were allowed to take a break and the experiment lasted approximately 45 minutes.

Results

Preliminary Analysis

One participant had 36 missing responses (comprising a quarter of all experimental trials) and was consequently removed from the analysis. A mean *A'* score was calculated across conditions, following Experiment 1, and screened for outliers. One individual was detected whose performance was over 2 *SD*s below the mean. This participant was also removed. The remaining 28 participants had missing or invalid responses on <3% of trials, on average, and these trials were removed from the analysis.

Task Performance

"Figure 3 about here"

The approach to data analysis matched Experiment 1 and *A'* scores are shown in Figure 3. A 2 (retention interval: 2 s vs. 10 s) x 3 (Distractor type: similar vs. dissimilar vs. no distractor) Bayesian repeated measures ANOVA was then conducted (see Table 3) and revealed some support for the model containing the retention interval. Mean performance declined from 0.80 (0.78, 0.82) at 2 s to 0.74 (0.72, 0.76) after 10 s, but there was no support for models containing the distractor effect or the interaction. The results of the Bayesian model comparison are shown in Appendix 2 and is congruent with the analysis of effects in Table 3.

"Table 3 about here"

Discussion

Replicating Experiment 1, there was support for the model containing the retention interval effect, with performance declining as the gap between the target and probe lengthened, yet the presence of the distractor did not noticeably affect performance or interact with retention interval length.

The absence of distraction does contrast with prior work (e.g. Blalock, 2013; Borst et al., 2012; Della Sala et al., 1999; Logie & Marchetti, 1991; Mercer, 2018), but there are several possible reasons for this. Firstly, the distractor was a passive event and participants were encouraged to ignore it. This may have reduced its effects, as Andrade et al. (2002) found that only attention-demanding interruptions impair memory. Yet whilst passive distraction may not exert a strong effect, it has been shown to have a detrimental effect in other studies (e.g. Blalock, 2013; Borst et al., 2012; Della Sala et al., 1999). The distractor itself was a limited event, being a single, isolated occurrence in a largely unfilled retention interval. Still, studies of the visual suffix effect have shown that one item, presented briefly, can hinder memory (see Hitch, Allen, & Baddeley, 2020; Parmentier, Tremblay, & Jones, 2004), and other studies have found interference from single, briefly presented distractors (e.g. Mercer, 2018).

Of more relevance may be the temporal position of the distractor. The distractor was placed half way into the retention interval and this arrangement allowed ample time to consolidate the representation, increasing its resilience to distraction. Smith, McKeown, and Bunce (2017) have shown that extending the interval between successive images in a visual recognition task improves performance and Ricker and Cowan (2014) argue that forgetting is greatly reduced when there is sufficient time to consolidate the items into memory. Alternatively, as the distractor was predictable (occurring at the same point in the retention interval), participants may have been able to more effectively manage it (e.g. through executive control mechanisms). Furthermore, if participants engaged in mind wandering during the retention interval (as was common in Experiment 1), they may not have fully encoded the distractor. This may have led to participants "zoning out" during the retention interval before refocussing for the probe.

Irrespective of the reason for the lack of distraction, time-dependent forgetting was still observed in Experiment 2. It should be noted that the magnitude of forgetting here was smaller than that recorded in Experiment 1 and there was only moderate support for the model containing the retention interval variable. There were methodological differences that may have been responsible for this difference (e.g. time for responding), and temporal distinctiveness may have played a role. In Experiment 1, a very brief ITI separated trials, whereas in Experiment 2 the ITI was longer. This extended ITI may have reduced interference from items experienced on earlier trials, but this possibility was directly assessed in Experiment 3.

Experiment 3

Both Experiments 1 and 2 showed forgetting over time, but the amount of memory loss differed – in the heterogeneous condition of Experiment 1, *A'* declined by 0.14 over the delay, whereas in Experiment 2 (using the distractor-free control as a comparison), the decline was 0.05. The aim of the final experiment was to explore whether a difference in the ITI length in the first two experiments may have influenced the amount of forgetting observed, and more generally compare decay and temporal distinctiveness theories.

Temporal distinctiveness models suggest that relative time is important (whereas decay models emphasise absolute time). One representative temporal distinctiveness account, known as SIMPLE (Scale Independent Memory, Perception and LEarning; Brown et al., 2007), states that items in memory are represented along a temporal dimension considered in relation to the point of retrieval. Recently experienced items are more distinct than older items, and the likelihood of recalling a memory depends upon its temporal proximity to other neighbouring memories. It is particularly difficult to recall items that were encoded in a crowded context, whereas temporal isolation of items should reduce forgetting (Geiger & Lewandowsky, 2008).

In Experiment 1, a low temporal distinctiveness situation was created due to the use of a short ITI (400 ms). This meant that the target object was temporally closer to the probe from the previous trial, rather than the current trial, especially in the 10 s condition. As such, the time-dependent forgetting observed in Experiment 1 may have been due to confusion caused by the temporal proximity of the old probe and the current target. In Experiment 2, where ITI was longer and temporal distinctiveness higher, forgetting over time was less pronounced. This final experiment intended to directly test whether temporal distinctiveness, as manipulated by ITI length, affected memory loss.

Previous investigations into temporal distinctiveness in visual memory have yielded mixed results. A possible role for temporal distinctiveness was reported by Shipstead and Engle (2013), who had participants remember arrays of coloured squares (four, six or eight objects). The array had to be retained across a delay of 900 ms or 3.9 s but, importantly, the ITI matched the length of the retention interval. This meant the distinctiveness of the items was equivalent in all conditions and estimated memory capacity did not decline at the longer retention interval (indeed, it was higher for the lengthier gap). A subsequent experiment used four possible combinations of the retention interval and ITI, finding that estimates of memory capacity increased when the ITI was longer (and decreased for longer retention intervals). Similarly, Mercer (2014) reported an improved ability to discriminate Fribbles at longer ITIs (in comparison to shorter ITIs).

These effects are compatible with temporal distinctiveness models, where longer ITIs reduce interference from older items and preserve the distinctiveness of current memories. However, Ricker, Spiegel, and Cowan (2014) offered an alternative explanation based on event segregation. This idea states that items are maintained in memory until the occurrence and detection of a new event. At this point, the current contents of memory are offloaded into long-term storage. At short ITIs, there may be a failure to complete offloading, meaning that interfering older items are retained within short-term memory, disrupting performance. At longer ITIs, events across trials are more effectively segregated. Consequently, Ricker et al. (2014) argue that an ITI effect alone cannot be taken to support temporal distinctiveness, which may actually be a trial spacing effect. A temporal distinctiveness effect would be manifested in an interaction between the retention interval and ITI, with absent forgetting at longer retention intervals in a high temporal distinctiveness context (i.e. a long ITI).

Ricker et al. (2014) could not find such an interaction. In their first experiment, three unfamiliar visual symbols had to be retained across delays lasting 1 s, 6 s or 12 s. Importantly, the ITI was also 1 s, 6 s or 12 s. The ability to detect changes to the target array declined at longer retention intervals, but there was no interaction between the two intervals. Time-dependent forgetting therefore occurred even with a lengthy ITI. Ricker et al. did find a main effect of ITI, with poorer performance at the shortest delay (1 s), but this was attributed to failed event segmentation. In a subsequent experiment, Ricker et al. used a blocked design in which four filler trials (featuring brief 1.5 s retention intervals and 1 s ITIs) preceded the trial of interest. The latter trials had retention intervals lasting 1.5 s or 6 s, and ITIs lasting 1 s or 12 s. Once again, performance declined over the retention interval, but there was no interaction. The effect of ITI was also absent, and Ricker et al. concluded that decay is responsible for short-term forgetting, not low temporal distinctiveness. Rademaker et al. (2018) also found that preserving temporal distinctiveness did not prevent time-based forgetting when participants were remembering the orientation of linear sine-wave gratings over retention intervals lasting 1 s or 4 s.

Conversely, Souza and Oberauer (2015) used a colour recall task and manipulated distinctiveness by changing the ratio of the retention interval and ITI (each interval could be short or long). They found that temporal distinctiveness offered a better explanation for the data than decay, as a long retention interval did not cause poorer performance if the ITI was also long.

Given contradictory findings in past work, it is important to further assess the role of temporal distinctiveness in short-term forgetting, but the main focus of this study was to determine whether the forgetting rates in Experiments 1 and 2 may have been influenced by the ITI length. Experiment 3 adopted a similar design to the heterogeneous condition of Experiment 1, with participants comparing two Fribbles over a delay of 2 s or 10 s. However, in this experiment the ITI was also varied, being either short (400 ms, as in Experiment 1) or long (matching the length of the retention interval, as in Experiment 2).

In addition, Experiment 2 varied whether the ITI duration was fixed or variable within a block of trials. Rademaker et al. (2018) have criticised blocked designs (e.g. where the ITI is consistent throughout a sequence of trials) as it introduces fatigue effects, but the use of fixed or variables ITIs also affects predictability (see Nimmo & Lewandowsky, 2006). That is, when ITI is fixed, participants can anticipate whether the next trial will begin rapidly or not, and potentially utilise different strategies as a result. Furthermore, in models such as SIMPLE participants can focus on specific dimensions, hence if the temporal dimension is predictable (e.g. the ITI is consistently long), it may be considered as part of the memory decision making process.

In the present experiment, the ITI duration was either fixed within a block or variable. If predictability of ITI is important, a long, fixed ITI should boost recognition performance and potentially reduce forgetting over the retention interval. Conversely, a variable ITI, or a short ITI, may not offer protection from temporal forgetting.

Method

Participants

Twenty-eight undergraduate psychology students (24 females and four males) took part. Volunteers were aged between 18 and 60 (M = 25.04, SD = 10.27) and reported normal or corrected-to-normal vision. Participants received participant pool credits for completing the experiment and provided written informed consent before undertaking the procedure.

Materials

The fixation cross, mask and Fribble stimuli were again used. In total, 288 Fribbles were employed for experimental trials, and an additional nine utilised on practice trials. The experiment was run within a small cubicle using a PC and SuperLab (Version 5) software. Stimuli were displayed on a HannsG HP191 19-in. LCD monitor and responses were recorded on a keyboard.

Design and Procedure

The experiment employed a 2 (retention interval: 2 s vs. 10 s) x 2 (ITI length: short vs. long) x 2 (ITI type: fixed vs. variable) repeated measures design. The procedure matched the no distractor condition of Experiment 2, except ITI was manipulated. The short ITI was 400 ms (matching Experiment 1) and the long ITI was equivalent to the length of the retention interval (matching Experiment 2). When the ITI was fixed, it remained consistent within a block of trials, whereas a variable ITI could be short or long within a block. This was designed to reduce predictability around when the next trial would begin. Trials were completed within ten separate blocks, completed in a random order. Four blocks had a 2 s retention interval and six had a 10 s retention interval. The procedure lasted approximately 45 minutes.

Results

Preliminary Analysis

Two participants had more than 10%+ missing responses and, following the approach of Experiments 1 and 2, were removed from the analysis. Mean *A'* was also calculated and screened for outliers, but none were detected. Twenty-six participants were retained in the final analysis and missing/invalid responses were rare (< 2.5% of total trials, on average), but removed from the data analysis.

Task Performance

"Table 4 about here"

A' scores were calculated and subjected to a 2 (retention interval: 2 s vs. 10 s) x 2 (ITI length: short vs. long) x 2 (ITI type: fixed vs. variable) Bayesian repeated measures ANOVA. This found substantial support for the model including the retention interval (see Table 4).

Performance at 2 s (*M* = 0.77 [0.74, 0.80]) was higher than at 10 s (*M* = 0.70 [0.67, 0.73]). There was also moderate support for the model including ITI type, but this was due to better performance when the ITI length was variable (*M* = 0.75 [0.72, 0.78]) rather than fixed (*M* = 0.71 [0.68, 0.74]). None of the other effects or interactions were supported, including the important interaction between retention interval and ITI length. As can be seen in Figure 4, forgetting occurred as the retention interval was lengthened and this was not affected by ITI length. The full Bayesian model comparison is shown in Appendix 3.

"Figure 4 about here"

Discussion

Experiment 3 replicated the time-dependent forgetting found in Experiments 1 and 2. Importantly, increasing temporal distinctiveness by lengthening the ITI had no beneficial impact on performance and did not reduce forgetting. These data contrast with some previous findings, but support Ricker et al. (2014). As noted above, the beneficial ITI effects found in previous experiments are open to re-interpretation. Specifically, both Shipstead and Engle (2013) and Mercer (2014) found performance improved when the ITI was longer, but as this can be interpreted through an event segmentation account, a temporal distinctiveness effect can only be demonstrated through an interaction. No such interaction was found in Experiment 3, with performance declining at a similar rate for both short and long ITIs.

Souza and Oberauer (2015) did find evidence for temporal distinctiveness, with performance in their visual task depending on the ratio between the retention interval and the ITI. There were salient methodological differences, however, with Souza and Oberauer's participants having to recall colour (rather than recognise complex objects) and remember multiple items within an array.

Participants also performed modestly better when the ITI was variable, rather than fixed. This effect was unexpected but could have been influenced by attention. For example, when the ITI was variable, the next trial could potentially start very suddenly and participants may have remained more focussed in this situation. Yet the ITI type itself was not capable of slowing or preventing forgetting, and its effect was limited.

General Discussion

The present study investigated time-dependent forgetting in visual short-term memory within the context of other factors, including physical distinctiveness (Experiment 1), distraction (Experiment 2) and temporal proximity across trials (Experiment 3). In all three experiments, the model containing the retention interval effect received support from the data, sometimes very strongly, and the ability to successfully compare a target and a probe declined as the retention interval was lengthened.

In Oberauer et al.'s (2018) consideration of benchmarks in working memory, time-dependent forgetting of visual material was considered too ambiguous and contradictory to be classed as a benchmark, yet the effects here were more consistent. These experiments show that time-dependent forgetting can be found when the task only requires retention of a single visual object, and when the retention interval is unfilled (apart from the presence of a mask). Still, it is likely that more dramatic forgetting would be observed if participants were required to retain more than one of the stimuli used here.

In the verbal memory literature, there is evidence against temporal forgetting (e.g. Berman et al., 2009; Lewandowsky et al., 2009; Oberauer & Lewandowsky, 2013), though recently Ricker, Sandry, Vergauwe, and Cowan (2020) did find evidence of time-based forgetting for verbal stimuli (arrays of letters). Interestingly, this effect was present in a variety of different scenarios, regardless of articulatory suppression manipulations, consolidation times and set sizes. This resembles the present findings, where time-based forgetting for visual stimuli was found under a variety of different conditions.

Additionally, the present data fit with some prior studies of visual memory (Gold et al., 2005; Hesse & Franz, 2010; Krill et al., 2-18; McKeown et al., 2014; Mercer & Duffy, 2015; Ricker & Cowan, 2010, 2014) and support temporal models of forgetting. Furthermore, the time-dependent forgetting found here was documented for individual stimuli, showing that even one object can be lost over a delay. This is important, as memory for a single item may be thought resilient to any forgetting (e.g. Pertzov et al., 2017), yet that was not the case. Additionally, the memory loss happened despite there being enough time for encoding and consolidation. The rate of forgetting may have been influenced by the complex stimuli employed, which comprised different appendages attached to a central body, and only parts of this object would change. Nonetheless, the present data add to a body of literature showing time-dependent forgetting for a variety of different visual material, from simple, individual features (Pertzov et al., 2013; Rademaker et al., 2018) to more complex stimuli like faces (Krill et al., 2018).

The retention interval effect uncovered here could be taken as evidence for decay, in which memories gradually degrade over time. McKeown et al. (2014) argue that decay does happen for actively maintained non-verbal representations, which become increasingly noisy over time. This degrades the quality of the memory trace. Yet in one leading model of decay – Time-Based Resource Sharing or TBRS (Barrouillet, Bernardin, & Camos, 2004) – memories decay as attention is directed elsewhere, but decay can be prevented through maintenance strategies. Here, however, any active maintenance attempts could not stop forgetting. Unlike some other studies, no attempt was made to stop rehearsal or refreshing, yet forgetting was still observed. This highlights the difficulty of retaining unfamiliar visual stimuli over brief delays and suggests that maintenance strategies may be ineffective for the type of stimuli used here (three-dimensional, complex and novel shapes). Furthermore, participants had to remember precise details about these stimuli, which may have increased the challenges of effectively memorising them.

While temporal forgetting was observed, the precise underlying mechanism remains unclear. As outlined above, the results are compatible with a decay process, but it is possible that any forgetting is much more rapid (e.g. sudden death; Zhang & Luck, 2009). The mechanism of decay also remains vague but could represent a change in the internal focus of attention. During the retention interval, participants should attend to the representation of the target, but participants may be more likely to engage in task-unrelated thought over a longer retention interval.

Unsworth and Robison (2016) have shown that task-unrelated thought during a visual working memory trial is associated with poorer performance than task-relevant thinking, and Soemer (2019) found that retention of nonverbal material over time is worse when task-unrelated thoughts occur. Furthermore, Soemer's participants engaged in more task-irrelevant thinking over longer retention intervals, which was correlated with poorer performance. The data from Experiment 1 showed that self-reported mind wandering was quite common in the procedure, indicating a possible role of task-unrelated thought in memory loss. While the frequency of mind wandering was not correlated with recognition accuracy in Experiment 1[1], this was based on relatively few data points. But attention may have played a role in Experiment 3, where task accuracy was higher when the ITI was variable and the start of

[1] Bayesian correlations were used to assess the relationship between performance in each condition of Experiment 1, overall self-reported mind wandering and mind wandering during each retention interval. All Bayes Factors (BF_{10}) were under 0.5 and usually compatible with the null hypothesis (<0.33).

trials less predictable, in comparison to fixed ITIs. Longer delays may be associated with reduced on-task thinking and higher mind wandering, and Soemer (2019) suggested that task-unrelated thought during the retention interval diverts attention away from the representation. This could lead to decay, in line with the TBRS model.

The present study cannot clarify the exact cause of the loss in memory precision, or whether it occurred gradually or rapidly, but forgetting did occur in the absence of any external interference. The other salient finding from the current study was the independence of forgetting. In all three experiments, there was no evidence for any interaction between the retention interval and other variables, showing that the memory loss was unrelated to these other factors. Indeed, while increasing stimulus similarity and varying the ITI duration had modest benefits for performance on the task, neither variable could slow forgetting. Similarly, temporally isolating trials by extending the ITI did not reduce the loss of memory.

These results are therefore problematic for pure interference models and temporal distinctiveness theory, suggesting that in some cases the absolute length of the retention interval does influence memory. In Experiment 2, a distractor did not affect performance, though it is possible that more substantial distraction or task-irrelevant interruptions would have a stronger effect. In Experiment 3, the relationship between the retention interval and ITI did not affect task accuracy, challenging temporal distinctiveness and offering support for a small but growing body of research in visual working memory (Rademaker et al., 2018; Ricker et al., 2014). As noted above, some effects consistent with temporal distinctiveness can be explained in a different way, using Ricker et al.'s (2014) event segmentation process. In addition, one of temporal distinctiveness theory's key predictions, concerning improved performance when temporal isolation is high, could be reinterpreted as a decay process (i.e. as the ITI is extended, there is more decay of older representations).

There were some limitations with the present study that could be improved in future research, including the number of trials. Data were based on 24 trials per condition (12 “Same” and 12 “Different”), which was intended to avoid making experiments overly long, given the lengthy delays used. However, future studies could aim to collect more data from each condition. The present study also used a blocked design, so trials with a short retention interval were completed separately to those with a longer retention interval. This was intended to reduce uncertainty for participants and limit the likelihood that they would become confused about when to respond, but this also made the block arrangement more predictable and may have influenced attention.

In conclusion, the present findings show clear time-dependent forgetting in visual short-term memory that is difficult to explain without reference to a temporal component. Future work should continue investigating the underlying mechanisms of temporal forgetting and consider whether internal distractions such as mind wandering contribute to memory loss.

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Declaration of Interest

The authors report no conflicts of interest.

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available in the article's supplementary materials.

References

Andrade, J., Kemps, E., Werniers, Y., May, J., & Szmalec, A. (2002). Insensitivity of visual short-term memory to irrelevant visual information. *Quarterly Journal of Experimental Psychology, 55*(3), 753-774. https://doi.org/10.1080/02724980143000541

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General*, *133*(1), 83-100. https://doi.org/10.1037/0096-3445.133.1.83

Barry, T. J., Griffith, J. W., De Rossi, S., & Hermans, D. (2014). Meet the Fribbles: Novel stimuli for use within behavioural research. *Frontiers in Psychology, 5*, 103. https://doi.org/10.3389/fpsyg.2014.00103

Berman, M. G., Jonides, J., & Lewis, R. L. (2009). In search of decay in verbal short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(2), 317-333. https://doi.org/10.1037/a0014873

Blalock, L. D. (2013). Mask similarity impacts short-term consolidation in visual working memory. *Psychonomic Bulletin & Review, 20*(6), 1290-1295. https://doi.org/10.3758/s13423-013-0461-9

Borst, G., Ganis, G., Thompson, W. L., Kosslyn, S. M. (2012). Representations in mental imagery and working memory: Evidence from different types of visual masks. *Memory & Cognition, 40*(2), 204-217. https://doi.org/10.3758/s13421-011-0143-7

Brady, T. F., Konkle, T., & Alvarez, G. A. (2009). Compression in visual short-term memory: Using statistical regularities to form more efficient memory representations. *Journal of Experimental Psychology: General, 138*(4), 487-502. https://doi.org/10.1037/a0016797

Brady, T. F., Konkle, T., & Alvarez, G. A. (2011). A review of visual memory capacity: Beyond individual items and toward structured representations. *Journal of Vision, 11*(5), 1-34. https://doi.org/10.1167/11.5.4

Brown, G. D. A., Neath, I., & Chater, N. (2007). A temporal ratio model of memory. *Psychological Review, 114*(3), 539-576. https://doi.org/10.1037/0033-295X.114.3.539

Campoy, G. (2012). Evidence for decay in verbal short-term memory: A commentary on Berman, Jonides, and Lewis (2009). *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*(4), 1129-1136. https://doi.org/10.1037/a0026934

Clapp, W. C., Rubens, M. T., & Gazzaley, A. (2010). Mechanisms of working memory disruption by external interference. *Cerebral Cortex, 20*(4), 859-872. https://doi.org/10.1093/cercor/bhp150

Della Sala, S., Gray, C., Baddeley, A., Allamano, N., & Wilson, L. (1999). Pattern span: A tool for unwelding visuo-spatial memory. *Neuropsychologia, 37*(10), 1189-1199. https://doi.org/10.1016/S0028-3932(98)00159-6

Farrell, S., Oberauer, K., Greaves, M., Pasiecznik, K., Lewandowsky, S., & Jarrold, C. (2016). A test of interference versus decay in working memory: Varying distraction within lists in a complex span task. *Journal of Memory and Language, 90*, 66-87. https://doi.org/10.1016/j.jml.2016.03.010

Geiger, S. M., & Lewandowsky, S. (2008). Temporal isolation does not facilitate forward serial recall – or does it? *Memory & Cognition, 36*(5), 957-967. https://doi.org/10.3758/MC.36.5.957

Gold, J. M., Murray, R. F., Sekuler, A. B., Bennett, P. J., & Sekuler, R. (2005). Visual memory decay is deterministic. *Psychological Science, 16*(10), 769-774. https://doi.org/10.1111/j.1467-9280.2005.01612.x

Hesse, C., & Franz, V. H. (2010). Grasping remembered objects: Exponential decay of the visual memory. *Vision Research, 50*(24), 2642–2650. https://doi.org/10.1016/j.visres.2010.07.026

Hitch, G. J., Allen, R. J., & Baddeley, A. D. (2020). Attention and binding in visual working memory: Two forms of attention and two kinds of buffer storage. *Attention, Perception, & Psychophysics, 82*, 280-293. https://doi.org/10.3758/s13414-019-01837-x

Jarmasz, J., & Hollands, J. G. (2009). Confidence intervals in repeated-measures designs: The number of observations principle. *Canadian Journal of Experimental Psychology, 63*(2), 124-138. https://doi.org/10.1037/a0014164

JASP Team (2018). JASP (Version 0.9.0.1) [Computer software]. Retrieved from https://jasp-stats.org/

Johnson, J. S., Spencer, J. P., Luck, S. J., & Schöner, G. (2009). A dynamic neural field model of visual working memory and change detection. *Psychological Science, 20*(5), 568-577. https://doi.org/10.1111/j.1467-9280.2009.02329.x

Kahana, M. J., & Sekuler, R. (2002). Recognizing spatial patterns: A noisy exemplar approach. *Vision Research, 42*(18), 2177-2192. https://doi.org/10.1016/S0042-6989(02)00118-9

Krill, D., Avidan, G., & Pertzov, Y. (2018). The rapid forgetting of faces. *Frontiers in Psychology, 9*, 1319. https://doi.org/10.3389/fpsyg.2018.01319

Lewandowsky, S., Oberauer, K., & Brown, G. D. A. (2009). No temporal decay in verbal short-term memory. *Trends in Cognitive Sciences, 13*(3), 120-126. https://doi.org/10.1016/j.tics.2008.12.003

Lin, P.-H., & Luck, S. J. (2009). The influence of similarity on visual working memory representations. *Visual Cognition, 17*(3), 356-372. https://doi.org/10.1080/13506280701766313

Logie, R. H., Brockmole, J. R., & Vandenbroucke, A. R. E. (2009). Bound feature combinations in visual short-term memory and fragile but influence long-term learning. *Visual Cognition, 17*(1-2), 160-179. https://doi.org/10.1080/13506280802228411

Logie, R. H. & Marchetti, C. (1991). Visuo-spatial working memory: Visual, spatial or central executive? In R. H. Logie & M. Denis (Eds.), *Mental images in human cognition* (pp. 105-115). Amsterdam: Elsevier. http://dx.doi.org/10.1016/S0166-4115(08)60507-5

Lohmann, J., Herbort, O., & Butz, M. V. (2013). Modeling the temporal dynamics of visual working memory. *Cognitive Systems Research, 24*, 80-86. https://doi.org/10.1016/j.cogsys.2012.12.009

Magnussen, S., & Greenlee, M. W. (1999). The psychophysics of perceptual memory. *Psychological Research, 62*(2-3)*,* 81–92. https://doi.org/10.1007/s004260050043

Magnussen, S., Greenlee, M. W., Baumann, O., & Endestad, T. (2010). Visual perception memory. In L. Bäckman & L. Nyberg (Eds.), *Memory, aging and the brain: A Festschrift in honour of Lars-Göran Nilsson* (pp. 53–75). Hove, UK: Psychology Press. https://doi.org/10.4324/9780203866665

Makovski, T., & Jiang, Y. V. (2008). Proactive interference from items previously stored in visual working memory. *Memory & Cognition, 36*(1), 43-52. https://doi.org/10.3758/MC.36.1.43

Makovski, T., Shim, W. M., & Jiang, Y. V. (2006). Interference from filled delays on visual change detection. *Journal of Vision, 6*(12), 1459-1470. https://doi.org/10.1167/6.12.11

Makovski, T., Watson, L. M., Koutstaal, W., & Jiang, Y. V. (2010). Method matters: Systematic effects of testing procedure on visual working memory sensitivity. *Journal* *of Experimental Psychology: Learning, Memory, and Cognition, 36*(6), 1466-1479. https://doi.org/10.1037/a0020851

Mate, J., & Baqués, J. (2009). Visual similarity at encoding and retrieval in an item recognition task. *Quarterly Journal of Experimental Psychology, 62*(7), 1277-1284. https://doi.org/10.1080/17470210802680769

Matsukura, M., Luck, S. J., & Vecera, S. P. (2007). Attention effects during visual short-term memory maintenance: Protection or prioritization? *Perception & Psychophysics, 69*(8), 1422-1434. https://doi.org/10.3758/BF03192957

McKeown, D., Holt, J., Delvenne, J-F., Smith, A., & Griffiths, B. (2014). Active versus passive maintenance of visual nonverbal memory. *Psychonomic Bulletin & Review, 21*(4), 1041-1047. https://doi.org/10.3758/s13423-013-0574-1

Mercer, T. (2014). The loss of short-term visual representations over time: Decay or temporal distinctiveness? *Journal of Experimental Psychology: Human Perception and Performance, 40*(6), 2281-2288. https://doi.org/10.1037/a0038141

Mercer, T. (2018). Retroactive interference in visual short-term memory. *Experimental Psychology, 65*(3), 139-148. https://doi.org/10.1027/1618-3169/a000401

Mercer, T., & Duffy, P. (2015). The loss of residual visual memories over the passage of time. *Quarterly Journal of Experimental Psychology, 68*(2), 242-248. https://doi.org/10.1080/17470218.2014.975256

Morey, C. C., Cong, Y., Zheng, Y., Price, M., & Morey, R. D. (2015). The color-sharing bonus: Roles of perceptual organization and attentive processes in visual working memory. *Archives of Scientific Psychology, 3*(1), 18-29. https://doi.org/10.1037/arc0000014

Nimmo, L. M., & Lewandowsky, S. (2006). Distinctiveness revisited: Unpredictable temporal isolation does not benefit short-term serial recall of heard or seen events. *Memory & Cognition, 34*(6), 1368-1375. https://doi.org/10.3758/BF03193278

Nosofsky, R. M., & Kantner, J. (2006). Exemplar similarity, study list homogeneity, and short-term perceptual recognition. *Memory & Cognition, 34*(1), 112-124. https://doi.org/10.3758/BF03193391

Oberauer, K., & Lewandowsky, S. (2013). Evidence against decay in verbal working memory. *Journal of Experimental Psychology: General, 142*(2), 380-411. doi:10.1037/a0029588

Oberauer, K., & Lewandowsky, S. (2014). Further evidence against decay in working memory. *Journal of Memory and Language, 73*, 15-30. https://doi.org/10.1016/j.jml.2014.02.003

Oberauer, K., Lewandowsky, S., Awh, E., Brown, G. D. A., Conway, A., Cowan, N., … Ward, G. (2018). Benchmarks for models of short-term and working memory. *Psychological Bulletin, 144*(9), 855-958. https://doi.org/10.1037/bul0000153

Oberauer, K., Lewandowsky, S., Farrell, S., Jarrold, C., & Greaves, M. (2012). Modeling working memory: An interference model of complex span. *Psychonomic Bulletin & Review, 19*(5), 779-819. https://doi.org/10.3758/s13423-012-0272-4

Parmentier, F. B. R., Tremblay, S., & Jones, D. M. (2004). Exploring the suffix effect in serial visuospatial short-term memory. *Psychonomic Bulletin & Review, 11*(2), 289-295. https://doi.org/10.3758/BF03196572

Pertzov, Y., Bays, P. M., Joseph, S., & Husain, M. (2013). Rapid forgetting prevented by retrospective attention cues. *Journal of Experimental Psychology: Human Perception and Performance, 39*(5), 1224-1231. https://doi.org/10.1037/a0030947

Pertzov, Y., Manohar, S., & Husain, M. (2017). Rapid forgetting results from competition over time between items in visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 43*(4), 528-536. https://doi.org/10.1037/xlm0000328

Peterson, D. J., & Berryhill, M. E. (2013). The Gestalt principle of similarity benefits visual working memory. *Psychonomic Bulletin & Review, 20*(6), 1282-1289. https://doi.org/10.3758/s13423-013-0460-x

Postle, B. R., D'Esposito, M., & Corkin, S. (2005). Effects of verbal and nonverbal interference on spatial and object visual working memory. *Memory & Cognition, 33*(2), 203-212. https://doi.org/10.3758/BF03195309

Rademaker, R. L., Park, Y. E., Sack, A. T., & Tong, F. (2018). Evidence of gradual loss of precision for simple features and complex objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 44*(6), 925-940. https://doi.org/10.1037/xhp0000491

Ricker, T. J., & Cowan, N. (2010). Loss of visual working memory within seconds: The combined use of refreshable and non-refreshable features. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*(6), 1355-1368. https://doi.org/10.1037/a0020356

Ricker, T. J., & Cowan, N. (2014). Differences between presentation methods in working memory procedures: A matter of working memory consolidation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*(2), 417-428. https://doi.org/10.1037/a0034301

Ricker, T. J., Sandry, J., Vergauwe, E., & Cowan, N. (2020). Do familiar memory items decay? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 46*(1), 60-76. https://doi.org/10.1037/xlm0000719

Ricker, T.J., Spiegel, L. R., & Cowan, N. (2014). Time-based loss in visual short-term memory is from trace decay, not temporal distinctiveness. *Journal of Experimental Psychology: Learning, Memory and Cognition, 40*(6), 1510-1523. https://doi.org/10.1037/xlm0000018

Ricker, T., J., Vergauwe, E., & Cowan, N. (2016). Decay theory of immediate memory: From Brown (1958) to today (2014). *Quarterly Journal of Experimental Psychology, 69*(10), 1969-1995. https://doi.org/10.1080/17470218.2014.914546

Sakai, K., & Inui, T. (2001). Characteristics of information decay in short-term visual memory and a diffusion model. *Japanese Journal of Psychology*, *72*(5), 404-412. https://doi.org/10.4992/jjpsy.72.404

Sanocki, T., & Sulman, N. (2011). Color relations increase the capacity of visual short-term memory. *Perception, 40*(6), 635-648. https://doi.org/10.1068/p6655

Saults, J. S., & Cowan, N. (2007). A central capacity limit to the simultaneous storage of visual and auditory arrays in working memory. *Journal of Experimental Psychology: General, 136*(4), 663-684. https://doi.org/10.1037/0096-3445.136.4.663

Shimi, A., & Logie, R. H. (2019). Feature binding in short-term memory and long-term learning. *Quarterly Journal of Experimental Psychology, 72*(6), 1387-1400. https://doi.org/10.1177/1747021818807718

Shin, H., Zou, Q., & Ma, W. J. (2017). The effects of delay duration on visual working memory for orientation. *Journal of Vision, 17*(14), 1-24. https://doi.org/10.1167/17.14.10

Shipstead, Z., & Engle, R. W. (2013). Interference within the focus of attention: Working memory tasks reflect more than temporary maintenance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39*(1), 277-289. https://doi.org/10.1037/a0028467

Sims, C. R., Jacobs, R. A., & Knill, D. C. (2012). An ideal observer analysis of visual working memory. *Psychological Review, 119*(4), 807-830. https://doi.org/10.1037/a0029856

Smallwood, J., & Schooler, J. W. (2015). The science of mind wandering: Empirically navigating the stream of consciousness. *Annual Review of Psychology, 66*, 487-518. https://doi.org/10.1146/annurev-psych-010814-015331

Smith, A. V., McKeown, D., & Bunce, D. (2017). Time manages interference in visual short-term memory. *Memory, 25*(8), 1117-1128. https://doi.org/10.1080/09658211.2016.1270967

Snodgrass, J. G., Levy-Berger, G., & Haydon, M. (1985). *Human experimental psychology*. New York, NY: Oxford University Press.

Soemer, A. (2019). Task-unrelated thoughts and forgetting in working memory. *Journal of Memory and Language, 106*, 118-134. https://doi.org/10.1016/j.jml.2019.03.004

Souza, A. S., & Oberauer, K. (2015). Time-based forgetting in visual working memory reflects temporal distinctiveness, not decay. *Psychonomic Bulletin & Review, 22*(1), 156-162. https://doi.org/10.3758/s13423-014-0652-z

Souza, A. S., & Oberauer, K. (2016). In search of the focus of attention in working memory: 13 years of the retro-cue effect. *Attention, Perception, & Psychophysics, 78*(7), 1839-1860. https://doi.org/10.3758/s13414-016-1108-5

Sun, S. Z., Fidalgo, C., Barense, M. D., Lee, A. C. H., Cant, J. S., & Ferber, S. (2017). Erasing and blurring memories: The differential impact of interference on separate aspects of forgetting. *Journal of Experimental Psychology: General, 146*(11), 1606-1630. http://dx.doi.org/10.1037/xge0000359

Tremblay, S., Nicholls, A. P., Parmentier, F. B. R., & Jones, D. M. (2005). Visual distraction and visuo-spatial memory: A sandwich effect. *Memory, 13*(3-4), 357-363. https://doi.org/10.1080/09658210344000422

Unsworth, N., & Robison, M. K. (2016). The influence of lapses of attention on working memory capacity. *Memory & Cognition, 44*(2), 188-196. https://doi.org/10.3758/s13421-015-0560-0

Viswanathan, S., Perl, D. R., Visscher, K. M., Kahana, M. J., & Sekuler, R. (2010). Homogeneity computation: How interitem similarity in visual short-term memory alters recognition. *Psychonomic Bulletin & Review, 17*(1), 59-65. https://doi.org/10.3758/PBR.17.1.59

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2006). The time course of consolidation in visual working memory. *Journal of Experimental Psychology: Human Perception & Performance, 32*(6), 1436-1451. https://doi.org/10.1037/0096-1523.32.6.1436

Wagenmakers, E.-J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., … Morey, R. D. (2018). Bayesian inference for psychology. Part II: Example applications with JASP. *Psychonomic Bulletin & Review, 25*(1), 58-76. https://doi.org/10.3758/s13423-017-1323-7

Xie, W., & Zhang, W. (2017). Familiarity increases the number of remembered Pokémon in visual short-term memory. *Memory & Cognition, 45*(4), 677-689. https://doi.org/10.3758/s13421-016-0679-7

Zhang, Q., Li, S., Wang, X., & Che, X. (2016). The effects of direction similarity in visual working memory: Behavioural and event-related potential studies. *Quarterly Journal of Experimental Psychology, 69*(9), 1812-1830. https://doi.org/10.1080/17470218.2015.1100206

Zhang, W., & Luck, S. J. (2009). Sudden death and gradual decay in visual working memory. *Psychological Science, 20*(4), 423-428. https://doi.org/10.1111/j.1467-9280.2009.02322.x

Appendix 1

Table A1

Bayesian Repeated Measures ANOVA Model Comparison for Experiment 1

Models	P(M)	P(M|data)	BF_M	BF_{10}	Error %
Null model (incl. subject)	0.20	1.17e-4	4.68e-4	1.00	-
Retention Interval	0.20	0.15	0.72	1307.88	1.59
Condition	0.20	2.95e-4	0.001	2.52	2.85
Retention Interval + Condition	0.20	0.63	6.74	5360.57	2.00
Retention Interval + Condition + Retention Interval x Condition	0.20	0.22	1.12	1869.01	1.43

Note. P(M) shows the prior model probabilities (pre-data) and P(M|data) shows probabilities after considering the data. BF_M indicates the change in the prior model odds following the assessment of the data and BF_{10} shows the Bayes Factor assessing the null hypothesis (values greater than 1 indicate support for the alternative rather than the null hypothesis, with higher values denoting higher levels of support for the alternative hypothesis).

Appendix 2

Table A2

Bayesian Repeated Measures ANOVA Model Comparison for Experiment 2

Models	P(M)	P(M|data)	BF_M	BF_{10}	Error %
Null model (incl. subject)	0.20	0.10	0.45	1.00	-
Retention Interval	0.20	0.81	17.38	8.06	4.01
Distractor	0.20	0.01	0.04	0.09	4.14
Retention Interval + Distractor	0.20	0.07	0.29	0.67	1.20
Retention Interval + Distractor + Retention Interval x Distractor	0.20	0.01	0.04	0.10	2.48

Appendix 3

Table A3

Bayesian Repeated Measures ANOVA Model Comparison for Experiment 3

Models	P(M)	P(M|data)	BF_M	BF_{10}	Error %
Null model (incl. subject)	0.05	3.30e-4	0.01	1.00	-
Retention Interval	0.05	0.11	2.27	339.01	0.71
ITI Length	0.05	8.51e-5	0.002	0.26	1.15
Retention Interval + ITI Length	0.05	0.03	0.59	96.57	2.27
Retention Interval + ITI Length + Retention Interval x ITI Length	0.05	0.01	0.15	24.16	4.10
ITI Type	0.05	9.25e-4	0.02	2.80	0.90
Retention Interval + ITI Type	0.05	0.44	13.83	1316.10	2.15
ITI Length + ITI Type	0.05	2.43e-4	0.004	0.74	1.64
Retention Interval + ITI Length + ITI Type	0.05	0.12	2.42	358.63	2.63

Models	P(M)	P(M|data)	BF $_{M}$	BF $_{10}$	Error %
Retention Interval + ITI Length + Retention Interval x ITI Length + ITI Type	0.05	0.03	0.53	86.19	2.75
Retention Interval + ITI Type + Retention Interval x ITI Type	0.05	0.12	2.43	360.63	2.10
Retention Interval + ITI Length + ITI Type + Retention Interval x ITI Type	0.05	0.03	0.62	100.63	3.76
Retention Interval + ITI Length + Retention Interval x ITI Length + ITI Type + Retention Interval x ITI Type	0.05	0.01	0.16	25.83	5.03
ITI Length + ITI Type + ITI Length x ITI Type	0.05	1.19e-4	0.002	0.36	2.96
Retention Interval + ITI Length + ITI Type + ITI Length x ITI Type	0.05	0.07	1.24	195.53	3.11
Retention Interval + ITI Length + Retention Interval x ITI Length + ITI Type + ITI Length x ITI Type	0.05	0.02	0.30	49.98	5.01
Retention Interval + ITI Length + ITI Type + Retention Interval x ITI Type + ITI Length x ITI Type	0.05	0.02	0.32	52.05	2.38
Retention Interval + ITI Length + Retention Interval x ITI Length + ITI Type + Retention Interval x ITI Type + ITI Length x ITI Type	0.05	0.004	0.08	13.02	3.74
Retention Interval + ITI Length + Retention Interval x ITI Length + ITI Type + Retention Interval x ITI Type + ITI Length x ITI Type + Retention Interval x ITI Length x ITI Type	0.05	0.002	0.03	5.05	6.58

Main Tables

Table 1

Number of participants responding "Yes, I am mind wandering" and "No, I am not mind wandering" in response to each probe.

	Probe 1	Probe 2	Probe 3	Probe 4	Probe 5	Probe 6	Probe 7	Probe 8
Yes	5	9	9	7	9	6	8	10
No	18	14	14	16	14	17	15	13

Note. Four participants responded to one or more of the mind wandering probes incorrectly (typically by continuing to use the S/D keys) and the analysis of these data was therefore based on the 23 respondents with complete data sets.

Table 2

Bayesian ANOVA Analysis of Effects in Experiment 1 and Effect Size (η_p^2)

Effect	P(incl)	P(incl|data)	BF Inclusion	η_p^2
Condition	0.40	0.63	4.10	0.18
Retention Interval	0.40	0.78	1894.58	0.43
Condition x Retention Interval	0.20	0.22	0.35	0.03

Note. The Bayesian analysis of effects is based on comparing different matched models. P(incl) shows the prior model probabilities and P(incl|data) shows probabilities after data have been assessed. The change from P(incl) to P(incl|data) gives $BF_{Inclusion}$. This can be used to assess evidence for retaining specific effects. Here, the model with the interaction is compared against the models without that interaction.

Table 3

Bayesian ANOVA Analysis of Effects in Experiment 2 and Effect Size (η_p^2)

Effect	P(incl)	P(incl|data)	$BF_{Inclusion}$	η_p^2
Retention Interval	0.40	0.88	8.00	0.26
Distractor	0.40	0.08	0.08	0.01
Retention Interval x Distractor	0.20	0.01	0.14	0.02

Table 4

Bayesian ANOVA Analysis of Effects in Experiment 3 and Effect Size (η_p^2)

Effect	P(incl)	P(incl|data)	$BF_{Inclusion}$	η_p^2
Retention Interval	0.26	0.76	447.19	0.35
ITI Length	0.26	0.18	0.28	0.06
ITI Type	0.26	0.58	3.83	0.20
Retention Interval x ITI Length	0.26	0.07	0.25	0.03
Retention Interval x ITI Type	0.26	0.18	0.28	0.04
ITI Length x ITI Type	0.26	0.10	0.54	0.08
Retention Interval x ITI Length x ITI Type	0.26	0.002	0.39	0.02

Figures

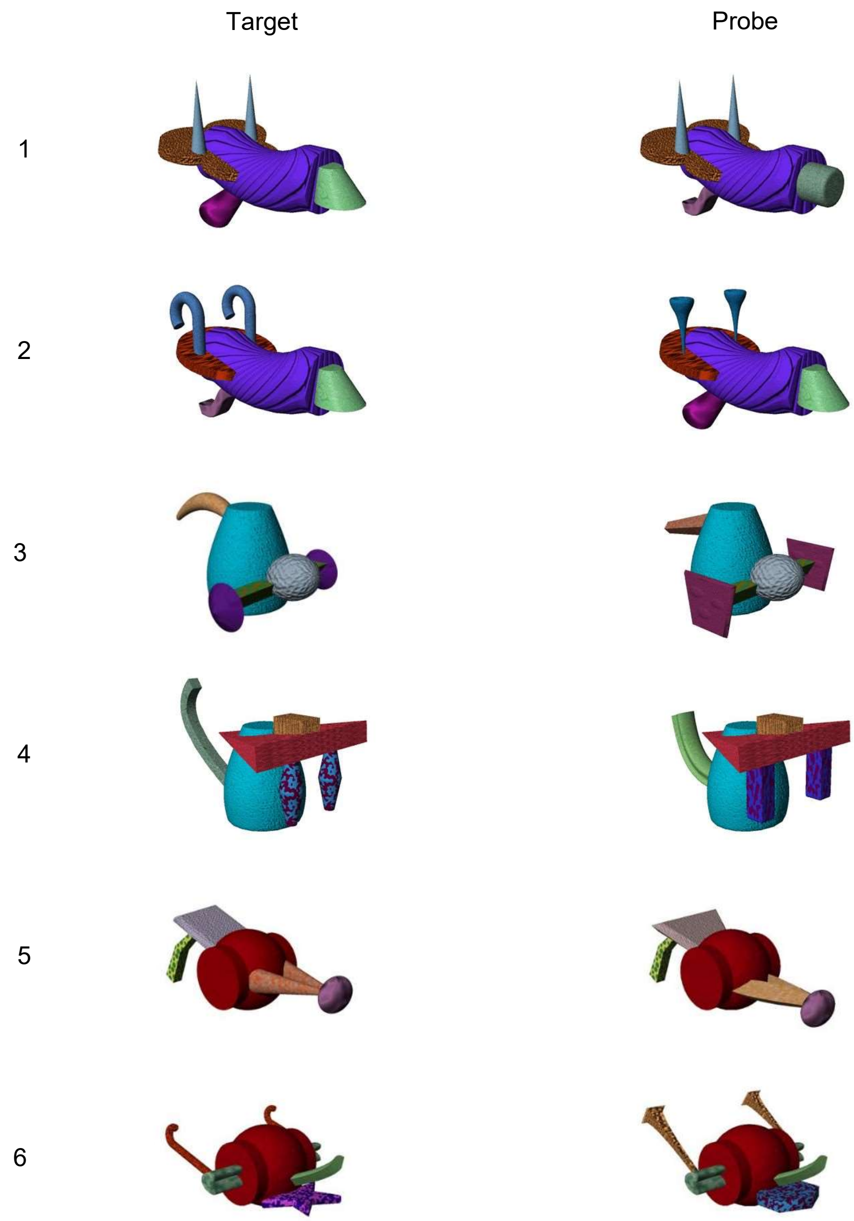

Figure 1. Each row shows an example target and probe. Here, all targets and probes are different in two of their appendages (on Same trials, the probe was identical to the target). The top two rows show species 4 of the "A" family, which was used for the homogeneous condition in Experiment 1. Rows 3 and 4 show examples from the "B" family and rows 5 and 6 show examples from the "C" family.

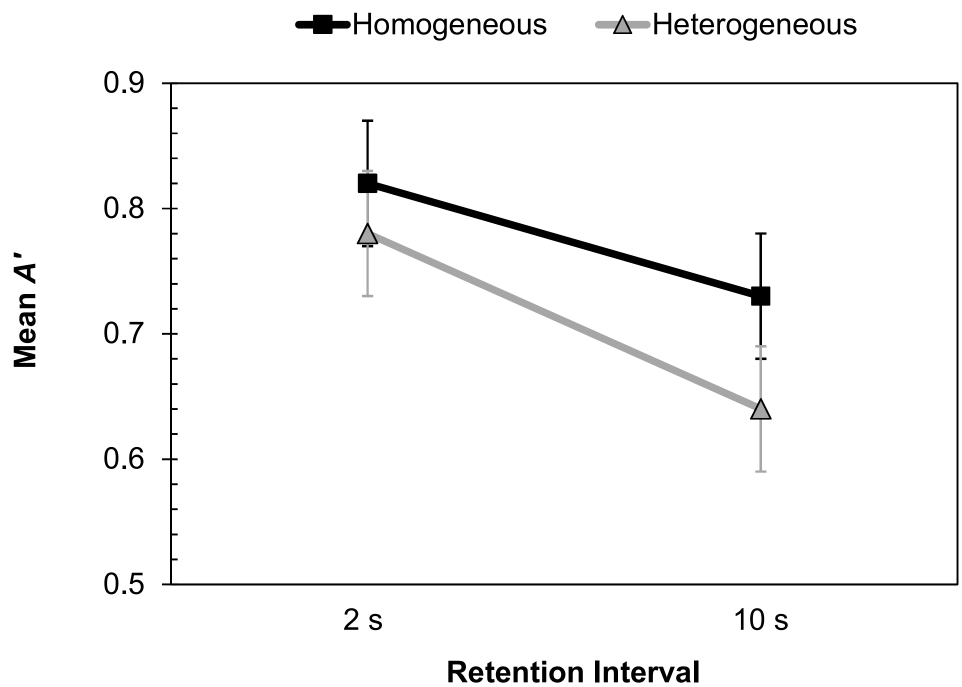

Figure 2. Experiment 1 results. Mean *A'* in the homogeneous and heterogeneous conditions at 2 s and 10 s retention intervals. Error bars show 95% *CI*s for a two-way repeated measures interaction (Jarmasz & Hollands, 2009).

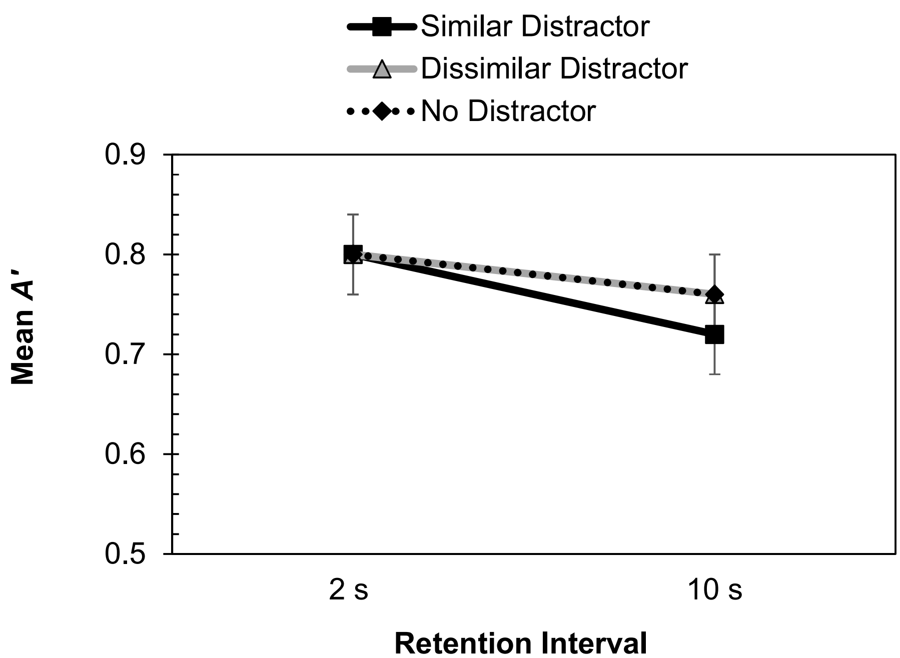

Figure 3. Experiment 2 results. Mean *A'* according to distractor type at 2 s and 10 s retention intervals. Error bars show 95% *CI*s for a two-way repeated measures interaction (Jarmasz & Hollands, 2009).

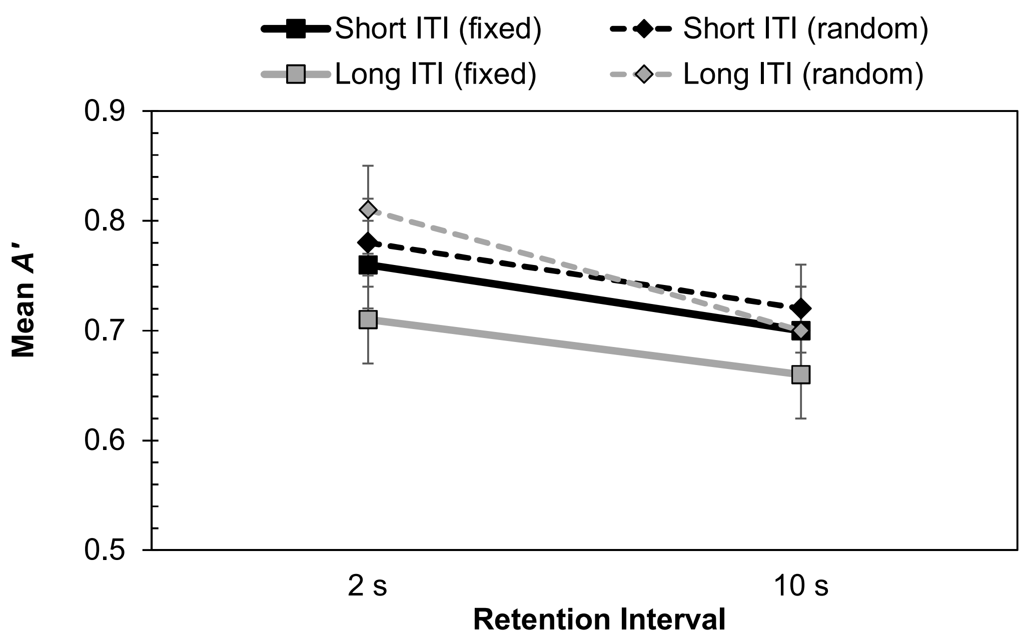

Figure 4. Experiment 3 results. Mean *A'* for 2 s and 10 s retention intervals, according to length of ITI (short vs. long) and ITI type (fixed vs. random). Low distinctiveness conditions are shown in black and high distinctiveness are shown in grey. Error bars show 95% *CI*s for a three-way repeated measures interaction (Jarmasz & Hollands, 2009).

Figure Captions

Figure 1. Each row shows an example target and probe. Here, all targets and probes are different in two of their appendages (on Same trials, the probe was identical to the target). The top two rows show species 4 of the "A" family, which was used for the homogeneous condition in Experiment 1. Rows 3 and 4 show examples from the "B" family and rows 5 and 6 show examples from the "C" family.

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